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FEASIBILITY OF INTERSTELLAR TRAVEL

by

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INTRODUCTION

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The prospect of interstellar exploration has aroused considerable speculation during the last 20 years. The earliest studies of relativistic rocket mechanics by Ackeret (Refs. 1 and 2), Tsien (Ref. 3), Bussard (Ref. 4), and others made two implicit assumptions that severely limit the performance of the vehicles considered. They assumed that the nuclear-energy rockets are limited to a single stage and that the available energy corresponds to a fixed fraction of the final vehicle mass. The latter assumption apparently arose from the thought that spent nuclear fuel would either be retained on board or dumped, rather than exhausted at high velocity. These assumptions are neither necessary nor desirable.

More recently, interstellar travel has been considered by Sanger (Ref. 5), Stuhlinger (Ref. 6), and von Hoerner (Ref. 7). They realized that the amount of available energy was a function of the propellant mass rather than the final vehicle mass; however, they did not consider staging the vehicles as is done with chemical rockets. They concluded, therefore, that interstellar travel using either fission or fusion nuclear reactions as an energy source is impossible because of fundamental limitations on the amount of available energy and that the photon (annihilation) rocket is necessary. In contradiction, this analysis shows that nuclear fission or fusion rockets can theoretically perform interstellar missions with reasonable flight times.

The problem of utilizing the full potential of fission or fusion nuclear reactions in a rocket engine is more difficult. The second portion of this paper considers some of the requirements of a fusion propelled vehicle to perform an interstellar probe mission.

AUTHOR

BASIC EQUATIONS FOR SINGLE-STAGE ROCKET

The basic equations for single-stage rocket propulsion at relativistic velocities were derived by Ackeret and have been utilized by subsequent workers. Ackeret's work is inexact, however, in that he considers the rest mass exhausted to equal the rest mass of fuel consumed. More exactly, the rest mass of fuel consumed is

$$M_f = M_{ex} + \epsilon M_f \tag{1}$$

where M_{ex} = rest mass exhausted and M_f = rest mass of fuel converted to kinetic energy. The initial rest mass of the vehicle is

$$M_0 = M_f + M_{b.o.} \tag{2}$$

where $M_{b.o.}$ is the rest mass of the vehicle at burnout.

Let

$$\chi = \frac{M_{b.o.}}{M_f} \tag{3}$$

Then

$$M_0 = M_f (1 + \chi) \tag{4}$$

The stage mass ratio is

$$\delta \equiv \frac{M_0}{M_{b.o.}} \quad \frac{1 + \chi}{\chi} \tag{5}$$

This is simply the result obtained with a chemical propulsion system.

To discuss the exterior energetics of the vehicle, a coordinate system fixed in space and a system relative to the vehicle may be used (Refs. 4, 5, and 6). By employing conservation of momentum, mass, and energy, and the Lorentz addition of velocities, Ackeret showed that the final vehicle velocity is given by

$$\frac{u}{c} = \frac{\delta^{2w/c} - 1}{\delta^{2w/c} + 1} \tag{6}$$

A relationship between the exhaust velocity and the fraction of fuel converted to energy gives the desired form for the final velocity. This is given by Sanger, Huth (Ref. 8) and Spencer (Ref. 9)

$$\frac{w}{c} = \left[\epsilon \; (2 - \epsilon)\right]^{1/2} \tag{7}$$

BASIC EQUATIONS FOR MULTISTAGE ROCKET

The kinematics of multistage relativistic rockets have been treated only by Subotowicz (Ref. 10); however, he did not examine energy requirements. As shown in Ref. 10, the burnout velocity u_n for the nth stage is given by

$$\frac{u_n}{c} = \frac{\prod_{j=1}^{n} \delta_j^{2w_j/c} - 1}{\prod_{j=1}^{n} \delta_j^{2w_j/c} + 1} \tag{8}$$

As in the classical case (Ref. 10), optimum staging occurs for equal step mass ratios or equal step burnout fractions if each step has the same exhaust velocity. Then Eq. (8) reduces to

$$\frac{u_n}{c} = \frac{\delta^{2n\,w/c} - 1}{\delta^{2n\,w/c} + 1} \tag{9}$$

where w/c is given in Eq. (7). Then

$$\lim_{n \to \infty} \frac{u_n}{c} = 1 \tag{10}$$

for a fixed step mass ratio. Thus, if enough stages are utilized, regardless of the exhaust velocity or mass ratio per stage, it is theoretically possible to attain a final velocity near that of light.

Another important aspect in the feasibility of interstellar travel is the final payload mass which can be delivered by a particular vehicle. Consider an n-stage vehicle with stage burnout rest mass $(\chi M_f)_j$ and stage structural or dead rest mass $(\beta M_f)_j$. Then the payload mass of the jth stage

$$(M_p)_j = (\chi M_f)_j - (\beta M_f)_j = (M_0)_{j+1} \tag{11}$$

the initial mass of the (j+1)th stage.

Generalizing Eq. (4)

$$M_{0_j} = M_{f_j} (1 + \chi_j) \tag{12}$$

Successive use of Equations (11) and (12) produces the overall payload to initial weight relation

$$M_p = \left[\frac{\prod_{j=1}^{n} (\chi_j - \beta_j)}{\prod_{j=1}^{n} (1 + \chi_j)} \right] M_{0_1} \tag{13}$$

Since the step fractions β_j and the stage fractions χ_j for optimum staging should be the same for all stages, Eq. (13) reduces to

$$\frac{M_p}{M_{0_1}} \equiv \Phi = \frac{(\chi - \beta)^n}{(1 + \chi)^n} \tag{14}$$

It may be of interest to determine the maximum vehicle burnout velocity for a given dead-weight fraction β and desired over-all payload fraction Φ. Algebraic solution for χ from Eq. (14) yields

$$\chi = (\Phi)^{1/n} \left[\frac{1 + \beta \left(\frac{1}{\Phi}\right)}{1 - (\Phi)^{1/n}} \right]^{1/n} \tag{15}$$

Substituting in Eq. (5) gives

$$\delta = \frac{1 + \beta}{\beta + \Phi^{1/n}} \tag{16}$$

and from Eq. (9)

$$\frac{u_n}{c} = \frac{\left(\frac{1 + \beta}{\beta + \Phi^{1/n}}\right)^{2\,nw/c} - 1}{\left(\frac{1 + \beta}{\beta + \Phi^{1/n}}\right)^{2\,nw/c} + 1} \tag{17}$$

Using Eq. (7), the final burnout velocity of the n-stage vehicle in terms of over-all payload fraction, deadweight fraction, and fraction of mass converted to energy, is

$$\frac{u_n}{c} = \frac{\left(\frac{1 + \beta}{\beta + \Phi^{1/n}}\right)^{2n\sqrt{\epsilon(2 - \epsilon)}} - 1}{\left(\frac{1 + \beta}{\beta + \Phi^{1/n}}\right)^{2n\sqrt{\epsilon(2 - \epsilon)}} + 1} \tag{18}$$

Figure 1 is a plot showing the over-all mass ratio required versus energy fraction ϵ for various final vehicle velocity ratios u_n/c. The over-all mass ratio is given by

$$\Delta \equiv \delta^n = \left(\frac{1 + \beta}{\beta + \Phi^{1/n}}\right)^n \tag{19}$$

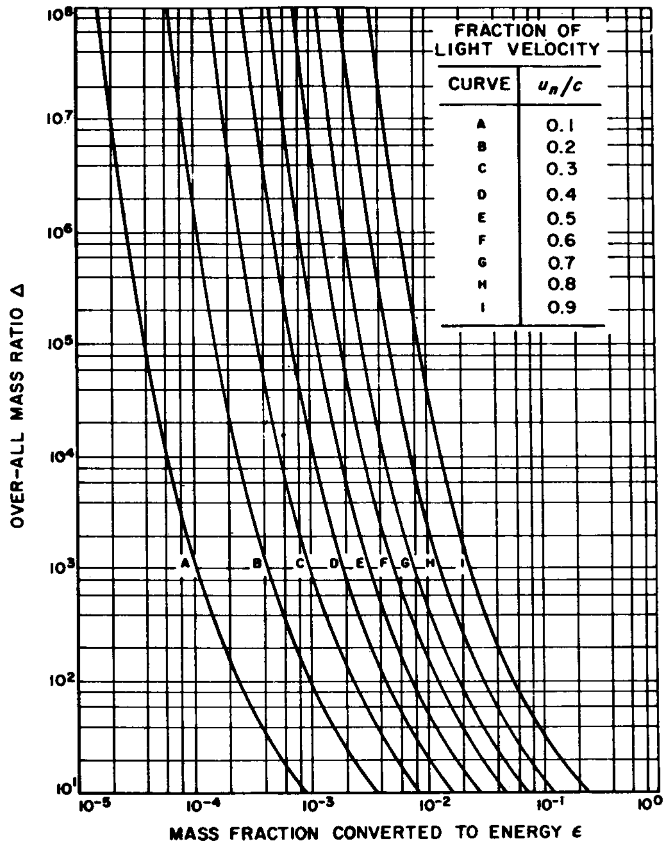

Fig. 1. Over-all mass ratio required versus energy fraction for various fractions of light velocity

EXAMPLES OF VELOCITIES AND TRANSIT TIMES

Following are some examples of velocities and transit times which may be attainable. The fraction of mass converted to energy by uranium fission is about 7×10^{-4}; by deuterium fusion, 4×10^{-3}. Table 1, obtained from Fig. 1, shows the over-all mass ratio Δ necessary to reach various velocities u_n/c for a fission rocket with $\epsilon = 7 \times 10^{-4}$. Table 2 shows the necessary mass ratio for a fusion rocket with an energy conversion fraction $\epsilon = 4 \times 10^{-3}$. If deceleration at the destination is required, the mass ratios must be squared; for a two-way trip with

Table 1. Mass ratios required for fission rockets, $\epsilon = 7 \times 10^{-4}$

Fraction of light velocity u_n/c	Required over-all mass ratio Δ		
	One-way trip, without deceleration	One-way trip, with deceleration	Two-way trip, with deceleration
0.1	1.4×10^1	2.0×10^2	3.8×10^4
0.2	2.2×10^2	4.8×10^4	2.3×10^9
0.3	4.1×10^3	1.7×10^7	- - -
0.4	9.0×10^4	8×10^9	- - -
0.5	2.1×10^6	- - -	- - -
0.6	[illegible]0 $\times 10^8$	- - -	- - -

Table 2. Mass ratios required for fusion rockets, $\epsilon = 4 \times 10^{-3}$

Fraction of light velocity u_n/c	Required over-all mass ratio Δ		
	One-way trip, without deceleration	One-way trip, with deceleration	Two-way trip, with deceleration
0.1	3.0×10^0	9.0×10^0	8.1×10^1
0.2	8.9×10^0	7.8×10^1	6.2×10^3
0.3	3.3×10^1	1.1×10^3	1.1×10^6
0.4	1.1×10^2	1.2×10^4	1.5×10^8
0.5	4.4×10^2	1.9×10^5	- - -
0.6	2.3×10^3	5.2×10^6	- - -
0.7	1.6×10^4	2.6×10^8	- - -
0.8	2.1×10^6	- - -	- - -
0.9	1.4×10^7	- - -	- - -

deceleration at each end, the mass ratios must be raised to the fourth power. These values are also shown in the tables.

Mass ratios of 10^3 to 10^6 seem quite feasible in principle. For unmanned probes, one-way trips without deceleration may well be adequate. Feasible velocity ratios corresponding to the mass ratios mentioned above are then 0.3 to 0.5 for uranium fission and 0.6 to 0.8 for deuterium fusion. The corresponding travel times depend on the acceleration used. If approximately 1-g acceleration could be achieved, relativistic velocities would be reached within a few months and the spacecraft could then coast to its destination at the velocity indicated above. To reach Alpha Centauri at 4.3 light years, the transit times would be 9 to 14 years with a fission rocket and 6 to 7 years with a fusion rocket.

Figures 2 to 4 show the attainable vehicle burnout velocity as a function of the number of stages for payload ratios of 10^{-1}, 10^{-3}, and 10^{-5} for a fusion rocket with $\epsilon = 4 \times 10^{-3}$. An interesting feature of these curves is the fact that a five-stage vehicle attains nearly the maximum possible velocity increment for a particular payload fraction.

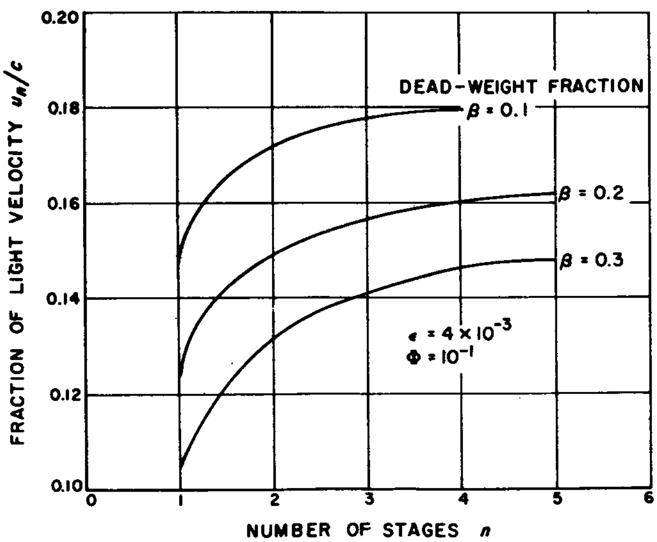

Fig. 2. Fractions of light velocity attainable for a deuterium fusion rocket versus number of stages for various dead-weight fractions (payload fraction $= 10^{-1}$*)*

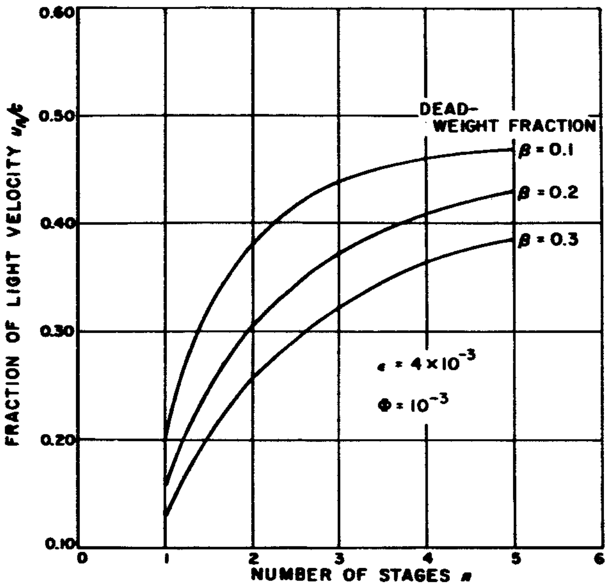

Fig. 3. Fractions of light velocity attainable for a deuterium fusion rocket versus number of stages for various dead-weight fractions (payload fraction = 10^{-3})

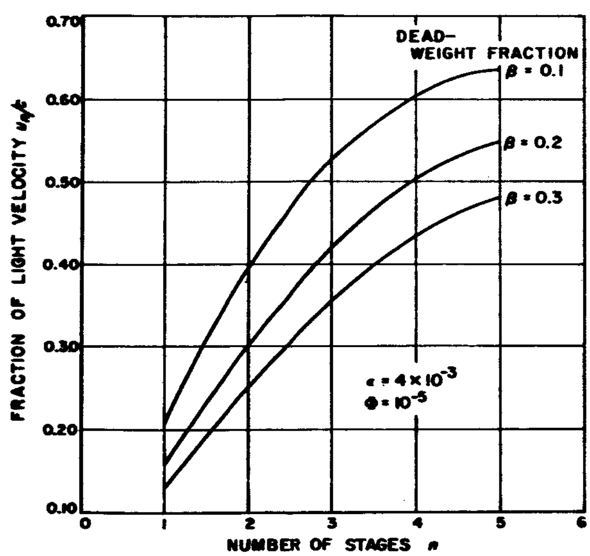

Fig. 4. Fractions of light velocity attainable for a deuterium fusion rocket versus number of stages for various dead-weight fractions (payload fraction = 10^{-5})

Figure 5 displays the effect of the dead-weight fraction β for a five-stage fusion rocket at various payload ratios. The relatively small effect of the dead-weight fraction upon performance is a very significant feature in the design of this type of system. It indicates that a strong effort should be made to obtain 100% burnup even at the cost of additional structural weight.

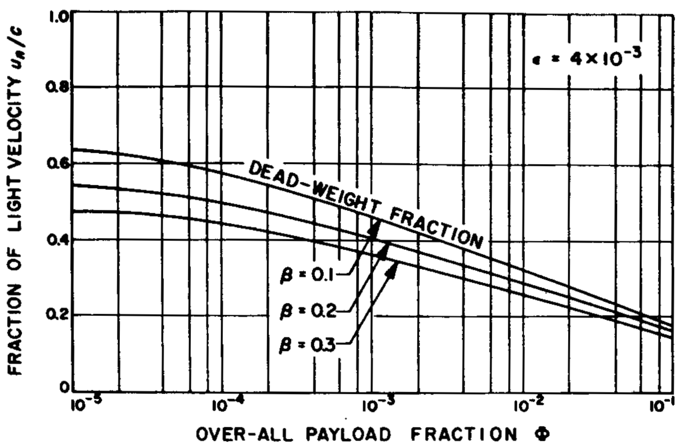

Fig. 5. Fractions of light velocity attainable for a five-stage deuterium fusion rocket versus over-all payload fractions for various dead-weight fractions

LIMITATIONS ON TRANSIT FOR A FUSION ROCKET VEHICLE

In general, the amount of fuel which can be utilized in a nuclear reaction is less than the theoretical limit. This is the so-called burnup fraction which is a number less than or equal to unity. The equation for the exhaust velocity of a particular stage can then be generalized to be

$$w = c \left[\epsilon b (2 - \epsilon b \right]^{1/2} \tag{20}$$

In order to determine the effect of burnup on system performance, we recall that for optimum staging, (Eq. 9),

$$\frac{u_n}{c} = \frac{\delta^{2 nw/c} - 1}{\delta^{2 nw/c} + 1} \tag{21}$$

Figure 6 shows the performance of a fusion vehicle with an acceleration of one g per stage, and a stage mass ratio of 10. It should be noted that unless burnups of greater than 1% can be achieved, there is little chance of the fusion vehicle performing interstellar missions to five light years with flight times less than 50 years.

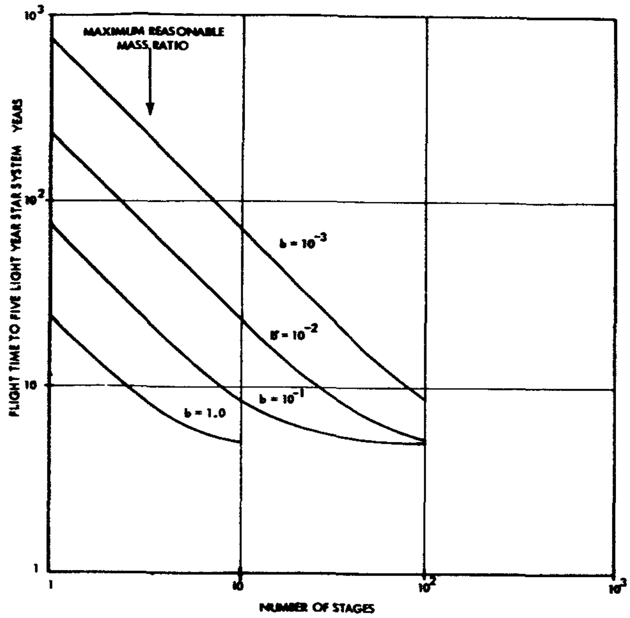

Fig. 6. Effect of incomplete burnup on the performance of fusion rocket vehicle

GENERAL CHARACTERISTICS OF A FUSION ENGINE

Figure 7 presents a schematic of a typical fusion engine. The basic components of the system are the fusion plasma, the superconducting coils, the structural vessels (including insulation), the refrigeration cycle, and waste heat radiators (not shown). A separate refrigeration system would be necessary to cool the superconducting coils from that used to cool the structure. For purposes of discussion, the heat load to the coils was neglected, and all energy escaping the plasma was assumed to be absorbed in the structure.

Now, the thrust of the engine is simply

$$F = \dot{m}_{ex}\, w \tag{22}$$

and the required fusion exhaust power is

$$P_{ex} = 10^{-13}\, F\, w/2 \tag{23}$$

The total power output from the fusion reactor is

$$P = \frac{P_{ex}}{1 - (\gamma + \alpha)} \tag{24}$$

where γ is the fractional power carried by the neutrons and α is the fractional power lost from the fuel due to bremsstrahlung and cyclotron radiation. The power which is absorbed in the engine walls is then

$$P_{abs} = \frac{\gamma + \alpha}{1 - (\gamma + \alpha)} P_{ex} \tag{25}$$

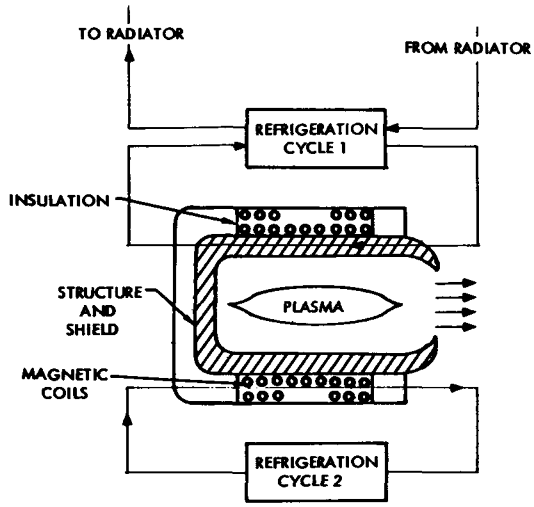

Fig. 7. Schematic of a fusion engine

As pointed out in Ref. 11, the D - He^3 reaction is of particular interest for rocket propulsion since the products are all charged particles, and thus, can be trapped by the external magnetic field. Now consider the competing reactions in such an engine (Ref. 12),

$$D + He^3 \longrightarrow \underset{3.6\ \text{Mev}}{He^4} + \underset{14.7\ \text{Mev}}{H} \tag{26}$$

$$\approx \begin{matrix}\text{50\% yield}\\ \text{of each}\end{matrix} \left\{ \begin{array}{ll} D + D \longrightarrow \underset{0.82\ \text{Mev}}{He^3} + \underset{2.45\ \text{Mev}}{n} & (27) \\ \\ D + D \longrightarrow \underset{1.01\ \text{Mev}}{T} + \underset{3.02\ \text{Mev}}{H} & (28) \end{array} \right.$$

$$D + T \longrightarrow \underset{3.5\ \text{Mev}}{He^4} + \underset{14.1\ \text{Mev}}{n} \tag{29}$$

If we neglect reaction (29), the fractional energy release which is imparted to the neutrons can be estimated. Let y represent the fuel fraction of He^3 and then (1-y) is the fuel fraction of D. Define the fraction of power carried by the neutrons as

$$\gamma \equiv \frac{P_{ne}}{P_t} \tag{30}$$

Then,

$$\gamma = \frac{0.5\,(1-y)^2\,(\overline{\sigma v})_{11}\,(2.45)}{y(1-y)\,(\overline{\sigma v})_{12}\,(18.3) + 0.5\,(1-y)^2\,(\overline{\sigma v})_{11}\,(7.3)} \tag{31}$$

where $\overline{\sigma v}$ determines the reaction rate for a Maxwellian velocity distribution.

The fractional energy lost by bremsstrahlung and cyclotron radiation, α, is defined as

$$\alpha = \alpha_{br} + \alpha_c \tag{32}$$

The equation for α_{br} (Ref. 17) is

$$\alpha_{br} = \frac{5.35 \times 10^{-31}\,N_e\,(N_1 Z_1{}^2 + N_2 Z_2{}^2)\,T_e'^{1/2}}{2.93 \times 10^{-12}\,N_1\,N_2\,(\overline{\sigma v})_{12}} \tag{33}$$

Rearranging and using the definitions of the He^3 and D fractions given above

$$\alpha_{br} = \frac{1.8 \times 10^{-19}\,T_e'^{1/2}\,(3y+1)\,(y+1)}{y(1-y)\,(\overline{\sigma v})_{12}} \tag{34}$$

The fractional power going into cyclotron radiation (Ref. 13) is approximately

$$\theta_c = \frac{8.5 \times 10^{-21}\left[(y+1)\,T'_i\,T'_e + (y+1)^2\,T'_e{}^2\right]\left(1 + \frac{T'_e}{204}\right)}{y\,(1-y)\,(\overline{\sigma v})_{12}} \tag{35}$$

Due to self absorption of the cyclotron radiation in the plasma and reflection from the chamber walls (if properly designed) the fractional power lost through this mode may be reduced. In the region of interest for these studies, the fractional energy lost is approximately 1% of θ_c thus

$$\alpha_c = 10^{-2}\,\theta_c \tag{36}$$

Figure 8 shows the fractional power entering the wall versus He^3 fraction in the fuel for various ion temperatures. In all cases an ion to electron temperature ratio of 2 is assumed. There appears to be an optimum operating temperature of 100-200 kev in the region from 0.5 to 0.7 He^3 fuel fraction. It should be noted, however, that the minimum fractional energy escaping the fuel is 20%. This simply means that 20% of the generated energy must be dumped by a thermal radiator. A similar problem has been well known to designers of gaseous fission power plants (Ref. 14).

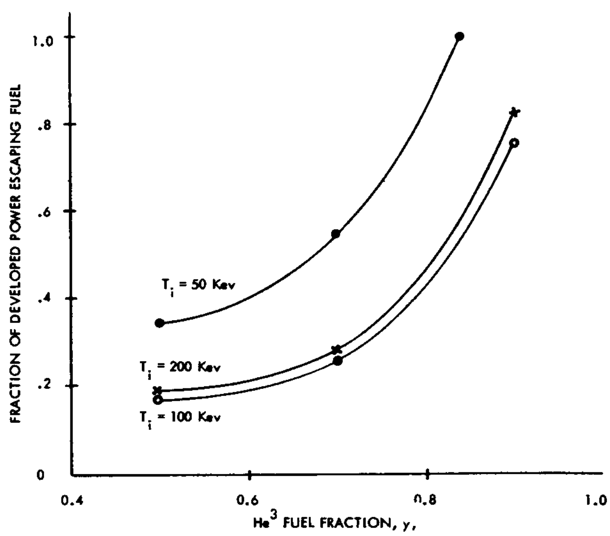

Fig. 8. Fractional energy loss from He^3-D plasma versus fuel fraction of He^3 at various plasma temperatures

The remaining equations which are necessary to determine the performance of the system will now be considered. The rest mass of fuel exhausted is generalized to

$$\dot{m}_{ex} = \dot{m}_f\,(1 - b\,\epsilon) \tag{37}$$

and the rest mass of fuel burned is

$$(\dot{m}_f)_b = b\,\dot{m}_f \tag{38}$$

But this is governed by the reaction rate in the chamber. Then, neglecting the DD and DT contributions,

$$(\dot{m}_f)_b = \left(\frac{m_1 + m_2}{N_{R_o}}\right) N_1 N_2 \,\overline{(\sigma v)}_{12}\, V_f \tag{39}$$

where V_f is the volume of the fuel.

The thrust is given by

$$F = \left(\frac{m_1 + m_2}{N_{R_o}}\right) N_1 N_2 \,\overline{(\sigma v)}_{12}\, V_f \,\frac{c}{g}\,(1-b\,\epsilon)\left(\frac{\epsilon\,(2-b\,\epsilon)}{b}\right)^{1/2} \tag{40}$$

If the engine thrust and size are specified (along with the reaction temperature), the required fuel concentration may then be determined from Eq. (40). This, in turn, sets the required magnetic field for confinement. Under optimum conditions, the confining magnetic field strength is simply

$$B = (8\pi\, N_t\, k\, T)^{1/2} \tag{41}$$

REFLECTION OF ENGINE CONSTRAINTS ON VEHICLE PERFORMANCE

In order to assess the potential of an actual vehicle, some estimate must be made of the major system weights. In this analysis, the weight of the engine chamber and waste heat radiator are considered. In this analysis, the engine structure is assumed to be tungsten. Since the strength to weight ratio of tungsten is a function of temperature, so also is the weight of the structure. The strength to weight ratio for tungsten is given in Eq. (42).

$$\rho / s = 7.45 \times 10^{-11}\; T_s^{\,0.6} \tag{42}$$

Due to the fact that the coolant must be heated from its temperature leaving the structure T_s to some radiating temperature, T_{rad}, the amount of heat to be rejected by the radiator is also a functioning of T_s. This may be seen by considering a simple refrigeration cycle where

$$P_{rad} = \frac{1}{\eta}\left(\frac{T_{rad} - T_s}{T_s}\right) P_{abs} + P_{abs} \tag{43}$$

For purposes of discussion, we assume an efficiency of the recrigeration system, η of 0.3. Then,

$$P_{rad} = P_{abs} \frac{(3.3\ T_{rad} - 2.3\ T_s}{T_s} \tag{44}$$

By extrapolating the results of Ref. 15, the weight of a belt type radiator is given by

$$W_{rad} = \frac{1.25 \times 10^{17}\ P_{rad}}{T_{rad}^5} \tag{45}$$

It is obvious that we wish to operate the belt at as high a temperature, T_{rad}, as possible. This temperature is then assumed to be 2500°K. Combining Eq. (44) and (45), the weight of the radiator is

$$W_{rad} = \frac{1.06 \times 10^4}{T_s}\ P_{abs}\ -2.94\ P_{abs} \tag{46}$$

The weight of the chamber structure is

$$W_s = \frac{}{s}\ R^3\ B^2 \tag{47}$$

or for a diameter of 10 m and an l/d of 2 (at a thrust level of 10^6 lbs.)

$$W_s = 2.05 \times 10^{-5}\ B^2 \left(\frac{V_f}{15.7 \times 10^8} \right) T_s^{\ 0.6} \tag{48}$$

By combining Eqs. (46) and (48), it is obvious that there is an optimum chamber coolant temperature, T_s. Then

$$\frac{dW_T}{dT_s} = 0 = - \frac{1.06 \times 10^{4}\ P_{abs}}{T_s^2} + 1.23 \times 10^{-5}\ B^2\ X$$

$$\left(\frac{V_f}{15.7 \times 10^8} \right) T_s^{\ -0.4} \tag{49}$$

After rearranging and solving for T_s, the optimum structural temperature is

$$T_s = \left[\frac{8.61 \times 10^8 \, P_{abs}}{B^2 \left(\frac{V_f}{15.7 \times 10^8} \right)} \right]^{0.625} \tag{50}$$

The minimum weight can then be determined by substituting this value of T_s into

$$W_T = \left(\frac{1.06 \times 10^4}{T_s} - 2.94 \right) P_{abs} \quad + 2.05 \times 10^{-5} \, B^2 \quad \frac{V_f}{15.7 \times 10^8} \quad T_s^{\,0.6} \tag{51}$$

Although all other system weights are neglected, this at least provides a basis from which the vehicle performance can be estimated.

In order to obtain the required vehicle characteristics, the gross payload necessary for an interstellar mission is estimated to be 10,000 lbs. The principal portion of this weight is necessary to provide telecommunications capability. Using X-band communication to a 200' terrestrial dish (Ref. 16), an information rate of 1 bit/min requires a 1 Mwe power transmitter at a distance of 5-10 light years. The auxiliary powerplant necessary to provide this power will probably weigh on the order of 2000 - 5000 lbs. This weight is consistent with the payload weight of 10,000 lbs. that has been assumed.

Figure 9 presents the flight time of a typical 5-stage fusion vehicle to deliver a 10,000 lb. gross payload to a five light-year distance. Notice that the required flight time is substantially longer than that shown previously since the dead weights of the chamber structure and radiator decrease the achievable stage mass ratio. The minimum flight time for a particular dead weight fraction per stage occurs with continuous propulsion and occurs with a burnup fraction of 0.15 in this case. Comparable results are obtained for other dead weight fractions. Increasing the initial weight of the vehicle also does not significantly decrease the required flight time.

Also shown is the required propulsion time to perform this mission. The propulsion time becomes longer with increasing burnup fraction, simply because the higher specific impulse of the engine produces lower thrust and thus vehicle acceleration at the same reactor power level. The initial acceleration for a burnup fraction of 10^{-2} is 3.7×10^{-3} g's and at $b = 0.15$, it is 1.3×10^{-3} g's.

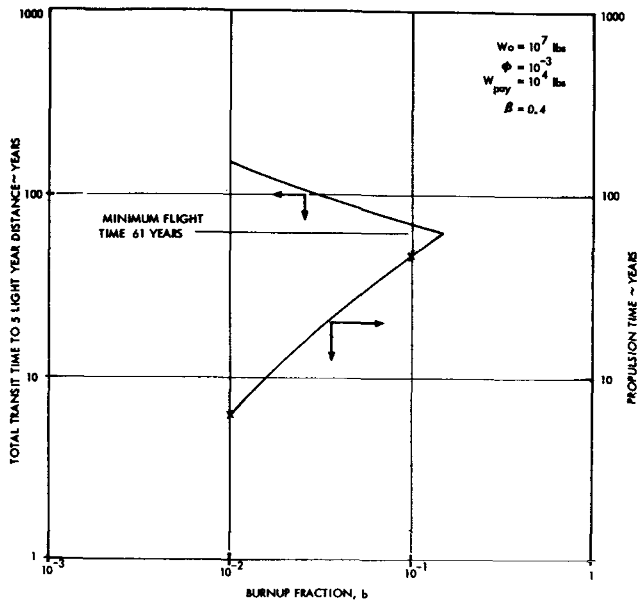

Fig. 9. Transit time to a 5 light year star with a 5 stage fusion vehicle

Figure 10 graphically demonstrates the engineering problems associated with the development of a system such as this. Confining magnetic field strengths from 200,000 to 300,000 gauss are required, even with the assumption of optimum confinement conditions. Finally, the power which must be dissipated in the radiator of the first stage is 40,000 - 50,000 M w. A typical radiator size at these power levels would be 1 square mile radiating from both sides. Thus from an engineering standpoint, some method to either decrease power losses or minimize the energy absorbed in the chamber walls is necessary in order that this system be feasible for interstellar missions.

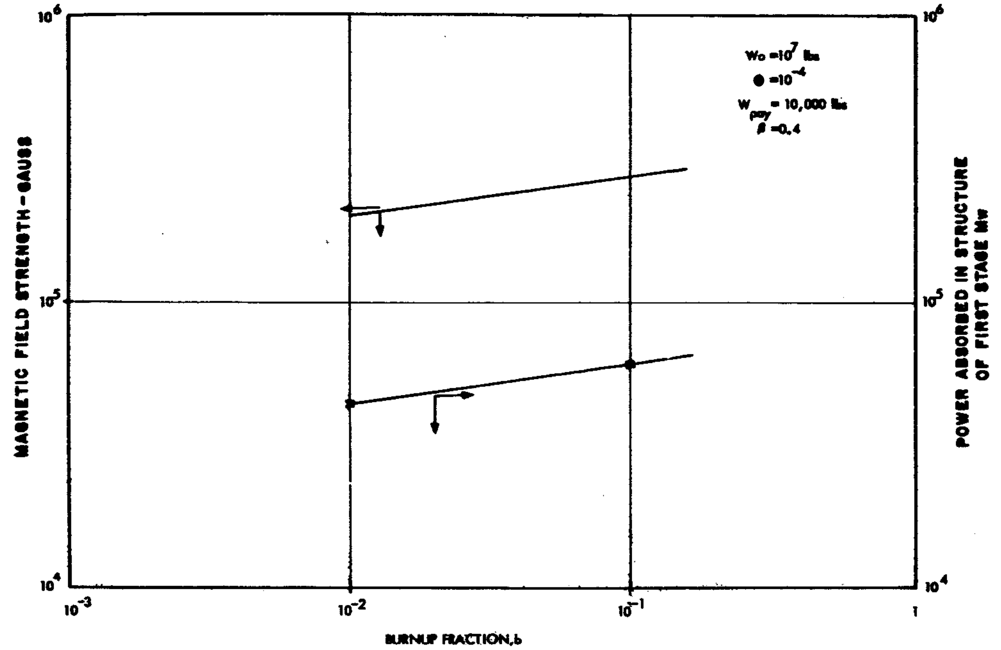

*Fig. 10. **Magnetic field strength and power absorbed in the structure versus burnup fraction for a fusion engine***

NOMENCLATURE

B	magnetic field strength, gauss
b	fuel burnup fraction
c	velocity of light = 3×10^{10} cm/sec
F	engine thrust, dynes
g	acceleration of gravity = 980 cm/sec^2
I	specific impulse, sec
j	stage number
k	Boltzmann constant = 1.38×10^{-16} erg |$^\circ$K atom
l/d	length to diameter ratio
M	rest mass, gm
$\mathfrak{M}$	molecular weight, gm/mole
$\dot{m}$	rest mass flow rate, gm/sec

N_{R_o}	Avogadros Number = 6.023×10^{23} atoms/mole
N	particle concentration, particles/cm^3
n	number of stages
P	power, Mw
R	radius of structural shell, cm
s	design stress of structure, dyne/cm^2
T	temperature, ^oK
u	burnout velocity, cm/sec
V	volume, cm^3
v	relative velocity of particles, cm/sec
W	weight, lb.
w	engine exhaust velocity, cm/sec
y	He^3 fraction of fuel
Z	atomic number
α	fractional power lost from fuel due to bremsstrahlung and cyclotron radiation
β	stage dead weight fraction
γ	fraction of power carried by neutrons
Δ	overall mass ratio
δ	stage mass ratio
η	efficiency of refrigeration system
θ	fractional power going into cyclotron radiation
ϵ	fraction of fuel mass converted to energy
ρ	density of structural material (tungsten), gm/cm^3
σ	microscopic reaction cross section, cm^2
Φ	over-all payload to initial vehicle weight ratio
χ	stage burnout weight fraction

SUBSCRIPTS

abs	absorbed
b	burned
b.o.	burnout
br	bremsstrahlung
c	cyclotron radiation
e	electron
ex	exhaust
f	fuel
i	ion
j	jth stage (j = 1 to n)
n	final stage
ne	neutron
p	payload
rad	radiator
s	chamber structure
t	total (fuel plus electrons)
o	initial
1	species 1 (D)
2	species 2 (He^3)

SUPERSCRIPTS

$\overline{}$	average value
	temperature in kev

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DISCUSSION

MR. LaROCCA (Propulsion Consultant, General Electric Company): I would like to know if you are employing relativistic mechanics and the time you are giving are vehicle "proper-times". Also: Is the vehicle arriving there with a velocity, let's say, 0.6 of the light velocity, or are you decelerating the vehicle when you arrive at the star configurations?

MR. SPENCER: Yes, we did use relativistic mechanics but as you can see, when you only talk about three-tenths the velocity of light, both time dilation and distance is very similar to the same old Newtonian mechanics. When you get up to six-tenths the velocity of light, this is a significant factor and it was taken into account in the equations. To your second question, most of these are fly-by missions then one would simply accelerate until you got to that velocity then coast the rest of the way. Well, a rule of thumb is that one G for one year will almost get up to the velocity of light. So you can see that when we are talking about six-tenths the velocity of light, if we accelerate at one G, the propulsion time would be less than a year. If you want to do an experiment which would require you to remain in the vicinity of that particular star, then you would have to decelerate perhaps, but we are talking here about probe missions, fly-by missions, similar to the Mariner.

CONCLUDING REMARKS

DR. SLAWSKY: I should like to take this opportunity to thank the speakers and the chairmen. This meeting would not have been what it is if it weren't for them.

Second, I would like to thank the General Electric Company for a superb job. They had support from the office of Aerospace Research, and I know how hard everyone worked on plans and arrangements for this symposium.

Finally, I would like to take this opportunity to let you know that the guiding spirit in our venture this year was Colonel Paul Atkinson. Though Colonel Atkinson is out of our office, he still keeps a very watchful eye over what we are doing.

This symposium will be very hard to beat. I thank you all very much.

. . . Whereupon at 12:55 p.m. the symposium adjourned . . . . .